DESIGN OF PASSIVE STRUCTURAL SYSTEMS TO RESIST HAZARD DIVISION (HD) 1.3 DEFLAGRATIONS

Joseph M. Serena, III, P.E.
Structural Engineer

Huntsville Division
US Army Corps of Engineers
Huntsville, Alabama

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ABSTRACT

HD 1.3 materials and munitions are those which do not mass detonate, but instead present a fire hazard and either a minor explosive hazard or a minor projectile hazard, or both. HD 1.3 materials usually burn quite vigorously, producing a rapidly expanding fireball. In relatively unconfined situations, the HD 1.3 material will burn but will produce no significant overpressures. In more confined situations, pressures may be sufficient to blow out typical blast-frangible panels. In either case, a HD 1.3 deflagration inside a building results in fireball that expands through doors, corridors, and windows, into areas of the building that might normally be considered to be well protected from conventional explosions.

The Huntsville Division, US Army Corps of Engineers, has developed a design guide for passive structural systems to resist the effects of HD 1.3 deflagrations. This design guide is based on both theoretical literature and actual test and accident reports, and contains methods for developing design criteria for structures. This paper summarizes the procedures and recommendations promulgated in the design guide. Basic HD 1.3 deflagration behavior is discussed. Design concepts for new structures and retrofitting existing structures are presented. The concept of confinement-type versus non-confinement-type structures is discussed. Recommendations are provided for production facilities, storage facilities, possible detonations, and fragment and firebrand hazards. Where applicable, computational design criteria procedures will be outlined. Future research and testing will also be discussed.

Introduction

Hazard Division (HD) 1.3 materials present unique requirements for facility design. Unlike mass-detonating explosives, HD 1.3 materials present little or no blast threat. Instead, these

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materials burn vigorously, producing a rapidly spreading fireball that can reach virtually any unprotected area and can be difficult or impossible to extinguish. Criteria are well defined for conventional, mass-detonating explosives. However, there is little criteria available to assist designers in developing facilities that provide adequate safety from HD 1.3 deflagrations. Therefore, the development of the HD 1.3 Passive Structural Systems Design Guide was undertaken. This paper presents the basic information contained in the Design Guide.

Purpose of the Design Guide

The purpose of this design guide is to provide criteria for the design of structures to provide adequate protection to personnel and assets from the hazards associated with production, handling, and storage of Hazard Division 1.3 explosives. It also provides guidelines for evaluating existing structures and facilities. It is called a passive structural systems design guide because structures are essentially passive protection systems. Active systems generally include high-speed sprinkler and ultra-high-speed deluge systems, which are designed to quench a fire and prevent propagation of the fire or explosion to adjacent stores of materials. Structural elements are passive systems in that they allow the fire to occur but prevent propagation of the fire or explosion by physically blocking the fire or channeling its effects away from personnel and assets to be protected.

The design guide is intended for use by structural engineers, architects, and facility planners who have experience in designing facilities to resist the effects of accidental explosions. Many of the terms, assumptions, and procedures are founded on the standard procedures for designing such structures, as defined in the tri-service technical manual, US Army TM 5-1300/Navy NAVFAC P-397/Air Force AFR 88-22, "Structures to Resist the Effects of Accidental Explosions" [1][1]. The design guide is intended to be used in conjunction with the methods and examples contained in TM 5-1300.

Development of the Design Guide

The first phase for development of the design guide was sponsored by the US Army's Project Manager for Ammunition Logistics, as part of the SAFELOAD program. Phase I included an extensive literature search to identify possible sources of data and information about the basic properties of HD 1.3 explosives; phenomena observed during deflagration events; and the interaction of these phenomena with structures and other enclosures. The literature search included an automated, keyword-based search of the National Technical Information Service (NTIS) and COMPENDIX literature databases. More than 1800 titles were located. A screening process was used to reduce the list to about 225 titles, and subsequent review of abstracts permitted further reduction in the number of documents to be reviewed in detail. Additionally, the proceedings of the 12th and 14th through 25th Explosive Safety Seminars, sponsored by the Department of Defense Explosive Safety Board (DDESB), were reviewed for applicable reports. A total of 60 references were ultimately acquired and studied to find information on accidents, laboratory and full-scale testing, and facility design criteria.

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[1]Numbers in square brackets denote references listed at the end of this paper.

The second phase of development was sponsored by DDESB. This effort was performed in-house by the Huntsville Division, US Army Corps of Engineers. The effort included a detailed review of all of the pertinent documents identified in Phase I. The goals were to identify specific descriptions, both quantitative and qualitative, about deflagrations of HD 1.3 substances; to define the phenomena involved; and to define as accurately as possible specific design criteria to provide for personal safety and protection of assets in the event of an HD 1.3 fire. The data acquired included both qualitative descriptions of HD 1.3 deflagrations and some specific numerical data. The data have permitted the definition of specific procedures and considerations for facilities subject to HD 1.3 deflagrations. Most useful in this development effort were the reports on deflagration experiments and actual HD 1.3 accidents. The majority of the accident reports were about accidents in production facilities. Although there is some bias of the design guide toward this type of facility, the procedures and recommendations are also applicable to storage and other facilities. The focus of the effort was primarily toward structural design and architectural features and layouts.

Contents of the Design Guide

This design guide is divided into four chapters. The first chapter provides an introduction to the purpose and scope of the design guide, the differences in classification of explosives, and the general behavior of HD 1.3 explosives in a fire or explosive event. Chapter 2 discusses criteria and procedures for designing new structures, including deflagration, detonation, fragment, and firebrand hazards. This chapter includes computational procedures for evaluating thermal effects and gas pressures from a deflagration and shock loads from a detonation. Examples problems illustrating these procedures are also included. Chapter 3 presents guidance and procedures for evaluating and modifying existing facilities. Chapter 4 includes general conclusions and recommendations, and suggestions for future study and research. Appendices include the Department of Defense quantity-distance standards for HD 1.1 and 1.3 materials, as defined in DOD 6055.9, "Department of Defense Ammunition and Explosives Safety Standards" [2]; and summaries of particularly pertinent accident and test reports. A complete list of all references is also provided; the length of this list precludes its being reproduced in this report.

Properties of Hazard Division 1.3 Explosives

Hazard Division 1.3 includes substances and articles which present a fire hazard, and either a minor explosive blast hazard or a minor projection hazard, or both. The definition of HD 1.3 materials states that they do not present a mass explosion hazard. Typical products in HD 1.3 include propellants and pyrotechnic munitions and devices.

When ignited in a unconfined state, HD 1.3 materials exhibit rapid burning, or deflagration. These substances include both fuel components and oxidizers. However, they are generally fuel-rich, non-stoichiometric mixtures. Therefore, these materials emit either flammable gases or fine particles of the material, or both, which are projected away from the donor. This unburned material then ignites as it comes in contact with air away from the donor material. This mechanism causes a large, expanding fireball or a rapidly moving flame front.

HD 1.3 substances and articles can be ignited by exposure to open flames, heat, shock, impact, pressure, friction, and electrostatic discharge or spark. Different materials have different sensitivities to each of these initiation stimuli. Also, the sensitivity of an explosive during manufacturing or processing can vary greatly at different stages of the manufacturing process, depending upon the components present in the mixture; type of configuration; wetness of the material; and the type of process being performed, e.g., pressing, grinding, mixing, etc.

The location of the ignition point can have an effect on the deflagration of the material. Initiation at or near the center of a mass will usually result in the most complete combustion and most hazardous or destructive effects. Ignition at the edge of the material can result in lesser effects, because the burning velocity of these materials is fairly slow, and locally high pressures may break up the mass before the reaction can pass completely through it.

Confinement of HD 1.3 materials by process containers, structures, or other enclosures, can dramatically increase the rate of reaction and the resulting effects. When enclosed, the rate of reaction is dependent on the vent area. Less venting and more confinement results in a faster, more violent reaction. Confinement within the structure also appears to increase the overall volume of the fireball. The presence of the structure increases the reaction rate in two ways. First, simply confining the reaction results in higher local pressures and temperatures, which accelerates the combustion reaction. Second, turbulence is induced in the flow of fuel particles and gases as they strike the structure, causing more complete mixing of fuel and air and, therefore, faster burning. The fireball expands out of the source structure or room, through any opening, travels down corridors, wraps around walls, and infiltrates any open space it can reach. The volume of this expanded fireball appears to be, in general, several times the volume of the fireball from an equivalent amount of material burning in open, unconfined conditions.

The pressures imposed by the deflagration flame front on structural elements are usually very small. There is usually no recognizable shock wave as is normally produced by high-order detonation. Normal frangible construction for explosives consists of walls or other elements that fail at an overpressure of 25 pounds per square foot (psf). Frangible elements of this type are not usually blown out or damaged by an HD 1.3 deflagration event. Instead, they act as barriers that reflect and redirect the flame front. For particularly fast-reacting materials, large quantities of material, or in poorly vented structures, local overpressures can sometimes be high enough to blow out frangible panels, or damage similarly lightweight construction close to the donor. The fireball usually escapes from the structure as high-velocity plumes jetting through the relatively small vent openings.

Some HD 1.3 materials can undergo a transition from a deflagration to a detonation, in which case the effects are virtually identical to the detonation of conventional high explosives. The only difference is the TNT equivalence of the material. Tests of naval gun and rocket propellants have shown that different HD 1.3 explosives can have widely varying TNT equivalencies. Other tests have shown that the TNT equivalency can vary with the method of initiation. Generally, initiation by contact with a relatively small booster charge of an HD 1.1

material can cause significantly higher explosive effects than initiation by a blasting cap, spark, or electric match. Also, depending on the geometry of the material mass or propellant grain, the entire mass of HD 1.3 material may not detonate. This occurs when the internal pressures blow the mass of explosive apart before the reaction can pass completely through the material. This results in blast effects that are less than those from a complete detonation and the projection of firebrands from the exploding mass.

It should also be noted that relatively large quantities of HD 1.3 material can be self-confining and this can result in faster deflagration. This occurs because the burning velocity of HD 1.3 materials is rather slow. In large quantities, burning internally, the surrounding mass of the material will confine the zone that is burning, increasing the reaction rate. In some cases, the confinement is such that detonation can occur. Therefore, for some materials, there is a mass or size threshold above which it is actually a mass detonating, HD 1.1 material. This has been observed in the explosion of large rocket motors, made of nominal HD 1.3 solid propellants, that have detonated with a significant TNT equivalence.

Confinement vs. Non-Confinement Structures

The design guide defines two basic types of structural configurations to be considered. These are confinement type and non-confinement type structures. A confinement structure is defined as a container, building, room, part of a structure, or other enclosure that sufficiently contains a deflagration to permit the development of significant gas pressures. A non-confinement structure is defined as one that provides sufficient venting to preclude the development of significant gas pressures inside the structure. The definition of "significant" gas pressures is subjective and requires some judgement on the part of the designer. In general, confinement structures will be relatively complete enclosures, with relatively low vent ratios. Conversely, non-confinement structures will be relatively open plan type structures, with relatively high vent ratios. Confinement structures will have only one, or only a few, vent paths or openings for the release of combustion gases. Non-confinement structures will have vent openings that are large, relative to the room or enclosure dimensions, and multiple paths for the expansion and escape of combustion products. In non-confinement structures, gas pressures generated in a HD 1.3 deflagration are very small, and the primary effect with is the fireball or flame spread. In confinement structures, both gas pressures and thermal effects must be considered in design.

There is not yet enough data available on the reaction of HD 1.3 materials to allow the development of a quantitative boundary between confined and non-confined events. There are simply too many different propellants and pyrotechnic mixes, and too many facility configurations, which have not been tested. Design of structures, therefore, to resist these effects and protect personnel and assets, requires some judgement on the part of the designer, or some direct knowledge of the characteristics of the particular explosive involved, and preferably both. The design guide does provide some qualitative guidelines for differentiation between the two structure types:

- If a structure is vented well enough to prevent confined gas pressures from exceeding

1-2 psi, then it can be considered to be a non-confinement structure.

- If a structure provides enough open, uncovered vent areas, such that any frangible panels close to the donor will not release, then it can be considered to be a non-confinement structure.

- Any roughly cubical enclosure, with an open vent area less than the area of one side of the enclosure, can be considered to be a confinement structure.

- A typical three-wall cubicle with no roof would probably be considered a non-confinement structure. A typical four-wall cubicle with a roof and a door would probably be considered a confinement structure.

It should be noted that the geometry of an enclosure is not the only factor defining its venting behavior. The weight or amount of explosive material involved also effects whether the room or enclosure is confinement type or non-confinement type. Very small quantities burning in large rooms can exhibit behavior the same as that for unconfined, open burning. Large amounts in very small but well vented spaces can be confined. Again, there is no specific quantitative boundary.

Design Procedures for HD 1.3 Facilities

Three procedures are provided in the design guide for developing design criteria. A procedure is provided to evaluate thermal (fireball) effects and determine the areas of the facility that will be threatened by a flame front. This procedure is applicable to both confinement and non-confinement structures. A separate procedure is given to compute gas pressures in confinement structures. A third procedure is provided for computing the approximate effects in the event of a transition from deflagration to detonation.

Design Procedure for Fireball Effects in Non-Confinement and Confinement Structures

The following procedure can be used to determine approximate extent of fireball effects inside a structure. The procedure includes some constants and equations that are general in nature and are believed to be conservative. However, these should be replaced wherever possible with information based on test data that is more reliably descriptive of the behavior of the particular HD 1.3 material. The procedure is as follows:

1) Determine the weight of explosive, W_{EXP}, that is involved in the event. In some cases the exact amount may not be known with certainty, so a reasonably conservative charge weight should be used. Also, although there is a specific total weight of material present, that material may deflagrate non-uniformly and produce firebrands, which are propelled away from the burning material. Without more specific data, however, the full weight of the material present should be included in W_{EXP}.

2) Apply a 20% safety factor to the charge weight; that is, multiply the actual weight by a

factor of 1.2. This factor accounts for uncertainties in the weight and properties of the explosive material, construction methods, quality of construction, etc. The use of this safety factor is consistent with standard practice for design of structures to resist explosions, as defined in TM 5-1300, and its use is reasonable here. The effective charge weight becomes

$$W_{EFF} = 1.2 \text{ X } W_{EXP}$$

3) Compute the equivalent diameter, D_{FIRE}, of a spherical fireball that would be expected from the rapid, open burning of the material. This can be conservatively computed as

$$D_{FIRE} = 10 \text{ X } W_{EFF}^{1/3}$$

where D_{FIRE} is in feet and W_{EFF} is in pounds.

4) Compute the volume of this spherical fireball:

EQUATION

$$V_{FIRE} = \frac{4}{3}\pi R_{FIRE}^3 = \frac{1}{6}\pi D_{FIRE}^3$$

where $R_{FIRE} = D_{FIRE} / 2$.

5) Apply a factor, F_1, to the fireball volume to account for the effect of confinement on the reaction rate and, therefore, on the effective volume of the fireball. In general, this factor can vary depending on the properties of the explosive material, the extent of the confinement, and the ratio of charge weight to room volume. There is not enough empirical data to rigidly define this factor. The use of an F_1 factor of 2 to 5 is recommended. The predicted volume of the fireball, V_{PRED}, can thus be computed as

$$W_{PRED} = F_1 \text{ X } V_{FIRE}$$

6) Determine the volume of the room or cubicle, V_{ROOM}, in which the event will occur. If the volume of the room is significantly greater than the predicted volume of the fireball, then the fireball should be completely contained inside the room. However, if the volume of the room is less than the predicted fireball volume, then the fireball will escape from the room. In this case, perform a sequential analysis of the paths that the fireball will take and the volumes available to the fireball for expansion. The procedure is as follows:

a. Compute the volume of the room or space enclosing the fire, V_{ROOM}.

b. Subtract V_{ROOM} from V_{PRED} to determine the remaining fireball volume,

$$V_{REM} = V_{PRED} - V_{ROOM}$$

c. Identify vents or openings through which the fireball can escape from the room.

d. Compute the area of each vent, A_{Vi}, and the total of these vent areas,

EQUATION

$$A_{TOT} = \sum A_{Vi}$$

e. Divide the remaining fire volume between the vents based on the relative vent areas, and compute the volume of the fireball passing through each vent,

EQUATION

$$V_i = \frac{A_{Vi}}{\sum A_{Vi}} V_{REM}$$

For each vent, V_i becomes the new V_{REM}, the remaining fire volume passing through that vent or area into other rooms or spaces.

This procedure is repeated for each fire path, and for each room or space in the facility, until the final extent of the fireball is determined. Use the assumption that the flame front will expand to entirely fill any space it reaches and that it will not blow out any frangible panels. When the fireball enters a corridor or hallway, divide the corridor into a series of segments. Use the area of the corridor (width x height) as the vent from the current segment to the next segment. When the fireball reaches an intersection of corridors, divide the fire volume between the downstream corridors. If a vent area leads into closed room or space, with no other vents, then subtract the volume of this space from V_{REM} before dividing the remaining volume between the other vent areas.

This procedure can be used to determine which areas of a structure are likely to be exposed to the thermal effects of an HD 1.3 fire. If the material involved has a significant TNT equivalence, then it may be more accurate to evaluate the accident as both a detonation and a

deflagration. The procedure includes the assumption that frangible panels do not release from their supports and do not, therefore, act as vents. However, for very large quantities of HD 1.3 materials, or for very weak construction, frangible panels close to the donor may release. This effect should be considered in the analysis.

This procedure can be used for both confinement and non-confinement structures. However, in confinement structures, the designer should consider the jetting effects of gases and flames escaping through the vent areas. In a highly confined situation, where V_{PRED} is much larger than the room volume, the flame front will exit the room as a high velocity jet or plume. This plume will proceed directly downstream for some distance before expanding laterally. If it impinges directly on frangible panels, the panels may release and provide an additional vent path that might not have occurred in a non-confinement structure.

Although the range of values for F_1 is somewhat arbitrary, it does represent an estimated range based on a review of the available test and accident report data. The test and accident data are rather limited, so conservative values for F_1 has been proposed. Pyrotechnic materials tend to burn much more vigorously than propellants, producing a much faster reaction, more heat, and a faster flame front. Some individual material components and mixtures in different stages of manufacturing are very reactive. For these cases a larger F_1 value may be appropriate. Future testing will be required to provide more specific guidance for selecting values for F_1. Again, there is no substitute for actual data about a specific HD 1.3 explosive material and its behavior. Such data should supersede any factors included in this procedure.

Design Procedure for Gas Pressures in Confinement Structures

In confinement type structures, both gas pressures and thermal effects must be considered. Thermal effects can be evaluated using the procedure defined above. The design for gas pressures is similar to the design of structures to resist high-order explosions. The primary difference is in determining the shock and gas pressures in the room. When a mass detonating material explodes inside a confinement structure, there is an initial shock overpressure on each structural element. Since the explosion is confined, the energy released by the explosion, along with the combustion products of the explosive material, increases the temperature and pressure of the atmosphere in the room, resulting in a quasistatic gas pressure. For HD 1.3 materials, the deflagration rate is usually slow enough that no real shock overpressure occurs. Instead, there will be a relatively fast rise to the peak gas pressure, which is substantially less than the peak shock overpressure from an equivalent weight of HD 1.1 material. For more energetic HD 1.3 materials, there may be a modified shock load with a non-zero rise time and a lower peak overpressure than for the same weight of HD 1.1 material. However, the controlling load case is usually the gas pressure.

The procedure for determining gas pressure loads in confinement structures, for the deflagration of HD 1.3 materials, is as follows:

1) Determine the weight of the HD 1.3 material, W_{EXP}, that is involved in the event.

2) Apply a 20 percent safety factor to the charge weight, so that the effective charge weight is

$$W_{EFF} = 1.2 \text{ X } W_{EXP}$$

3) Determine/compute the duration of the fireball. For most HD 1.3 materials, the duration of the deflagration can be computed as

$$T_{FIRE} = 0.2 \text{ X } W_{EFF}^{1/3}$$

where W_{EFF} is in pounds and T_{FIRE} is in seconds. This is a very conservative duration for most solid propellants and is probably excessively long for most pyrotechnic materials.

4) Determine the internal gas pressure time history, using the procedures in TM 5-1300.

These procedures are derived from experimental data for high explosives, and are based on the equivalent weight of TNT. To use these procedures, compute an equivalent charge weight, W_{EQ}. For HD 1.3 materials that are expected to burn but not detonate, W_{EQ} can be computed as

EQUATION

$$W_{EQ} = \frac{\phi[H^c_{EXP} - H^d_{EXP}] + H^d_{EXP}}{\phi[H^c_{TNT} - H^d_{TNT}] + H^d_{TNT}} \times W_{EFF}$$

where

W_{EQ} = equivalent charge weight for gas pressure

W_{EFF} = effective weight of the HD 1.3 material in question

H^c_{EXP} = heat of combustion of the HD 1.3 material in question

H^d_{EXP} = heat of detonation of the HD 1.3 material in question

H^c_{TNT} = heat of combustion of TNT = 5.05 E+06 ft-lb/lb = 15.1 MJ/kg

H^d_{TNT} = heat of detonation of TNT = 1.97 E+06 ft-lb/lb = 5.90 MJ/kg

ϕ = TNT conversion factor (from TM 5-1300, Figure 2-166)

If H^d_{EXP} is not known, the equivalent weight can be computed as

EQUATION

$$W_{EQ} = \frac{H^c_{EXP}}{H^c_{TNT}} \times W_{EFF}$$

5) Compute the leakage pressures outside of the donor enclosure using the procedures in TM 5-1300.

The gas pressure loads computed using this procedure can be used to design the confinement structure, including walls, roof, doors and vents, using the methods in TM 5-1300. The concept of confinement means keeping the primary structural elements in place to ensure that the overpressure, fragmentation, and thermal effects are directed away from potentially threatened areas, and to prevent personnel injury from building debris or structural collapse. Therefore, the structure should be designed to remain in place, although significant damage can be allowed to occur.

The pressure-time curve resulting from this procedure has a zero rise time and a fairly long duration. This instantaneous rise to peak pressure is typical of high-order detonations. For HD 1.3 materials, when there is no detonation, there is actually a finite amount of time between ignition and when peak pressure is reached. This rise time will generally be only a small fraction of the total gas pressure duration. This is especially true for large W_{EFF} in rooms with very little venting. Therefore, the use of a single-triangular pulse with a zero rise time is reasonable, in the absence of any other data on burn rates for the material. Alternately, the value of T_{FIRE} computed above can be used as the rise time to peak gas pressure.

Iteration of this process may be necessary to provide adequate protection from overpressures and optimize vent areas and frangible panel sizes. The designer can vary the size of the vents, to reduce the peak gas pressure and/or duration, in order to produce a more economical structural design and still direct combustion effects away from personnel and assets.

Computer programs are available which automate the gas pressure load calculations in TM 5-1300. The program SHOCK [3] can be used to compute the initial reflected shock load and impulse on a wall floor or roof of the structure. The program FRANG [4] can then be used to determine the gas pressure time-history, given the equivalent charge weight and room or building dimensions and vent data. FRANG can accommodate both covered and uncovered vents. Both SHOCK and FRANG are approved for use by DDESB. The computer program INBLAST [5] can also be useful in determining gas pressure loads for HD 1.3 facilities. INBLAST computes gas pressures for multiple-room layouts in which the rooms are

interconnected with multiple vents. The program also includes the option to use time-dependent burning instead of detonation. This program has not yet been approved for use by DDESB, and it should be used with appropriate care.

Design for Detonation of HD 1.3 Materials

Some HD 1.3 materials will transition from deflagration to a high-order detonation, especially when present in highly confined situations, in large quantities, or in especially vigorous initiation scenarios. The design of structural elements to resist an HD 1.3 material explosion, and provide an adequate level of protection, is the same as that described in TM 5-1300. The design is based on the TNT equivalence of the explosive material involved. If the specific TNT equivalence of a propellant is known, then the design is straightforward. However, if no TNT equivalence is known, the designer can compute a TNT equivalence based on the ratio of heats of detonation. The equivalent charge weight is computed as

EQUATION

$$W_{EQ} = \frac{H^d_{EXP}}{H^d_{TNT}} W_{EXP}.$$

If no value is known for the heat of detonation of the material, the equivalent charge weight can be approximated, using the ratio of heats of combustion, as

EQUATION

$$W_{EQ} = \frac{H^c_{EXP}}{H^c_{TNT}} \times W_{EXP}.$$

The 20 percent factor of safety should also be applied to these effective charge weights for detonation. The effective charge weight becomes

$$W_{EFF} = 1.2 \text{ X } W_{EQ}$$

The designer should take care to use a given TNT equivalence realistically. In many instances, the TNT equivalence is based on a boostered test, in which a small, mass-detonating charge is used as the initiator. This explosive charge appears to create a sympathetic detonation of all or part of the HD 1.3 material present. The TNT equivalence determined from this kind of test is higher than the equivalence for initiation by spark, friction, or other less violent methods. If the TNT equivalence is based on a boostered test, then the material in

process may not realistically be expected to mass detonate as energetically, or at all, when subjected to less violent stimuli. Another factor effecting the propensity of an HD 1.3 material to detonate is the size of the charge. There is a critical diameter, or critical depth, for each material. Individual charges, or materials on a conveyor, with dimensions less than the critical diameter will deflagrate, but will not propagate an explosion. This property is useful in designing processing steps and equipment, because it allows the designer to prevent explosion propagation by limiting the size and depth of material streams.

Designing a structure for a detonation, even if a detonation is unlikely, is the most conservative approach with respect to pressure loads. In the absence of any real data on the behavior of an explosive material, the designer may choose this approach. However, the thermal effects and gas pressures from a deflagration must still be evaluated to ensure adequate protection if the explosive burns instead of detonating.

Storage Facilities for HD 1.3 Materials

The methods discussed above were developed primarily from data on production facilities. Clearly, these procedures may not be completely applicable to the storage of large quantities of HD 1.3 material. Large quantities are usually stored in earth-covered igloos or other types of magazines. These structures provide significant confinement to the material during combustion. However, storage situations rarely provide a threat to personnel. Storage is controlled by the requirements in DOD 6055.9-STD. The purpose of these requirements is to prevent propagation of a fire or explosion from one storage building to another. Tests have shown that in storage-type structures, for large quantities of HD 1.3 propellants, the material can burn quite violently, creating enough internal pressure in the structure to blow out doors cause some local structural failures. The principal phenomenon is a high velocity jetting fireball that exits the magazine structure through the front door and wall. Storage buildings should be located to prevent this kind of fire jet from impinging on adjacent structures. Detonation of large quantities of HD 1.3 materials, in storage situations, has resulted in explosive effects that are almost equal to HD 1.1 explosions. In these cases, the overpressure damage to surrounding buildings was on the same order as that from HD 1.1 explosions. Care must be taken to ensure that only compatible explosives are stored together, in order to reduce the chance of detonation of HD 1.3 materials in storage.

Fragmentation Hazards

Detonation of conventional explosives can create hazardous fragment projectiles. Primary fragments are caused by the explosion of a cased charge. The fragments result from the shattering of the container that is in direct contact with the explosive material. The container can be the metal casing around explosives in conventional munitions, or metal containers used in manufacturing or storage. Primary fragments are characterized by very high initial velocities, on the order of thousands of feet per second. Usually, large number of very small, chunky fragments are produced. Secondary fragments are produced when a shock wave from an explosion strikes other objects located near the donor explosive. These objects include pieces of machinery, equipment, or building debris. Secondary fragments are

characteristically large, irregularly shaped projectiles with initial velocities on the order of hundreds of feet per second.

Primary fragments can be produced by detonation of an HD 1.3 material. In a mass fire in a munition or rocket motor, the overpressures inside the casing can become high enough to shatter or rupture the casing. Similarly, extremely rapid deflagration of a propellant or pyrotechnic material in a mixing bowl or feed hopper can create fragments from the container. Certainly, if a fire in these situations transitions to a detonation, primary fragments can result. There is no data available that describes how this differs from fragmentation from an HD 1.1 munition. The most reasonable approach is to assume a complete detonation of the HD 1.3 material. An effective charge weight can be computed using the equations provided above. This charge weight can then be used with the methods in TM 5-1300 to determine critical fragment criteria for design. If no data on the specific HD 1.3 material is available, the designer can conservatively assume that the material is TNT and that all of the material detonates.

Secondary fragments are likely to result only from a detonation of HD 1.3 material or from burning of a relatively large quantity in a well-confined structure. The procedures for determining size, velocity and trajectory of secondary fragments, given in TM 5-1300, can be used for HD 1.3 materials. For a detonation, the procedure is straightforward. The only difference is the use of a modified effective charge weight, which can be computed using the equations provided above. For deflagration of a large or well-confined charge, there are no specific guidelines on how to modify the procedures in TM 5-1300. The most conservative approach to assume that a detonation occurs. In some cases, the rupture of a process container, during a deflagration, may not be identical to a normal munition detonation. For example, a mixing bowl may break into only a few large pieces instead of many small fragments. These pieces should be treated as secondary fragments with initial velocities that are higher than normal.

The design of structural elements to defeat fragment hazards, from an HD 1.3 accident, are identical to those for a conventional (HD 1.1) accident, defined in TM 5-1300. Defeating primary fragments generally requires providing some kind of barricade or shield to intercept the fragments and prevent them from reaching acceptor personnel or assets. This requires design of a protective structure with sufficient thickness to stop the fragments. Secondary fragments pose an additional problem with their larger weights. The protective structure must be able to withstand the large forces generated by the impact of a heavy projectile moving at a fairly high velocity.

Firebrand Projectiles

Firebrands are burning or non-burning pieces of energetic material, packaging or dunnage that are thrown clear of a burning or detonating mass. They can present a threat to adjacent operations or assets by propagation of the fire as well as a hazard to personnel. There is virtually no test data available that defines the propensity of HD 1.3 explosives to produce firebrands, nor which defines size and velocity of firebrands. The available data does not

show that firebrand projection is a problem in conventional production-type facilities. Firebrand velocities are normally less than 1000 feet per second. The density of explosive materials is much less than that of normal fragmenting materials, such as steel. Therefore, firebrands are not penetrating fragments. No specific criteria is available for designing structural elements to defeat firebrands. The designer may make some assumptions about size, velocity, and weight of firebrands, and then perform a typical fragment projectile analysis.

Firebrands can be thrown in any direction away from the donor material. If firebrands are anticipated, then the designer must consider how to prevent firebrands from reaching any nominally protected areas. In relatively open facilities, firebrands can pass through doorways and vents and over walls to enter adjacent spaces. These firebrands can be stopped by placing additional wells or barricades in front of large openings, e.g., open walls of cubicles. Smaller shields can be placed in front of vent openings. Also, a cage or mesh can be placed over large openings. The openings in the mesh can be sized to intercept firebrands above a certain size. This mesh will stop firebrand projectiles, but will still provide significant vent area. In confinement structures, most firebrands will be retained inside the containment room, where they will burn and contribute to the overall gas pressure. Some may be thrown free through the vents. A blast door, a barricade in front of an open doorway or vent, or just locating all protected areas away from a direct line-of-sight through the vents, will provide adequate protection.

Features to Defeat Deflagraion and Detonation Effects

There are a number of architectural and structural features to consider in both new design and evaluation of existing facilities. These are predominantly features of the facility that can contain or redirect the effects of a deflagration and prevent these effects from reaching personnel or other explosive materials.

Fire Walls or Blast Walls: A fire wall or blast wall can be used to deflect the thermal effects of the HD 1.3 event. The wall must be located to completely deflect the flame front. That is, it must be a full-height panel that effectively seals off the exposed operation or personnel from the flame front, or increases the flame front travel distance sufficiently to effectively move the threatened operation out of range. In many HD 1.3 deflagrations, the overpressures are so small that hardened blast walls may not be required. Conventionally constructed walls, with an appropriate fire rating, can provide adequate protection from thermal effects. If fragmentation is a major concern, then a more substantial wall may be required. Fire-rated partitions provide little or no resistance to either primary or secondary fragments. Using frangible walls for protection not recommended, because a transition from deflagration to detonation, or an unexpectedly vigorous deflagration, may blow out a frangible panel and open up a path directly from donor to receiver.

Blast Doors: A facility may include blast doors that are designed to either contain or exclude the overpressure effects of an explosion. Blast doors can provide significant protection from a fireball, fragment or firebrand threat. However, they must be well sealed to

prevent leakage of fire around the edges of the door. Also, the doors must be closed to provide any protection. Modifying operating procedures to ensure the doors are closed may be necessary. Blast doors will also provide protection from effects of a HD 1.3 detonation. Steel blast doors can be designed to intercept and stop primary fragments, although this usually takes a considerable door thickness.

Non-Blast Doors and Doorways: Most facilities include conventional, non-blast doors which can be made of a number of materials. In situations where only a deflagration is expected, conventional fire-rated doors can be used to block fireball effects. However, such doors offer little protection from fragmentation and virtually no resistance to overpressures. Flammable doors will not provide much protection from fire because they can become a source for propagation of the fire. There are often doorway openings, or "manways", that do not include doors. The effects of a deflagration or detonation can easily pass through these openings. Designers should consider adding fire-rated or blast-resistant doors where necessary to provide adequate protection. In confinement situations, or when a detonation or significant fragment threats are anticipated, only blast-resistant doors should be used.

Windows: Many production type facilities include windows or viewports for monitoring remotely controlled operations. Most of these are blast-resistant windows that are made of layered, tempered glass or high-strength polycarbonate materials. They are usually capable of resisting significant blast pressures. Consequently, they usually are not frangible in the event of a deflagration, and they may even remain intact after an explosion.

Frangible Elements: Frangible wall or roof panels are generally designed to blow out under fairly low pressures and provide venting from an explosion. Normal frangible panels are designed to release at about 25 psf. However, most HD 1.3 deflagrations will not produce high enough pressures to blow out these panels. Unless an extremely vigorous deflagration or detonation is expected, frangible elements can be considered to remain in place. This assumption is conservative for flame effects, since it will result in a prediction of flame spreading inside the building and further from the source. The use of frangible panels can be limited to applications where high overpressures from a detonation or a confined deflagration are expected.

Vents: The fireball from a HD 1.3 deflagration will expand into any open space it can reach. Therefore, it is possible to protect personnel and assets by providing an open vent path out of the structure. For example, adding an open vent at the end of a corridor can prevent the flame front from turning the corner or reduce its travel distance past the corner. Vents from one room into another location inside a building are not recommended; wherever possible, deflagrations should be vented directly to the outside of the building. Vent stacks can be added, especially in well-confined situations, to provide a specific path for overpressure and fire effects. Open vents are preferred over covered vents. Vent panels or closures are essentially frangible panels that will blow out under a given overpressure. Conventional frangible panels may not release in a deflagration unless the HD 1.3 material is particularly energetic and the vents are located in the immediate vicinity of the material. Therefore, covers over vents must be designed to release under very low overpressures. It is recommended that vent

covers for deflagrations have a resistance of no more than 2.5 psf [6].

Fragmentation Shields: Virtually any substantial structural element can be considered a fragment shield. Primary fragments can be defeated by concrete walls, blast doors, and specifically located shield plates, if the material thickness is sufficient. Frangible panels and conventional walls and doors do not usually provide enough material thickness to stop primary fragments. Secondary fragments are larger and travel at slower speeds, so the mass of an element is more important in stopping secondary fragments than its thickness. Firebrands also travel at relatively low velocities. Any substantial element may stop projected firebrands.

Personnel Exits: In a number of accidents involving HD 1.3 materials, personnel who were located in a threatened area were able to escape serious injury because they were located near exits from the facility. Clearly, if personnel have a clear exit from the building and enough time to reach that exit, many injuries and fatalities can be prevented. The location of normal and emergency exit doors should be carefully considered. Locating personnel close to exits, or locating exits near personnel workstations, should be accomplished whenever possible. Sufficient exits should be added wherever necessary to ensure that personnel have unobstructed paths for egress from the building.

Sprinkler and Deluge Systems: Although not considered passive systems, sprinkler and deluge systems should clearly be considered to provide adequate levels of protection. An ultra-high-speed deluge system can extinguish burning HD 1.3 material, or at least reduce the thermal effects output, if it can detect the start of the combustion and react quickly enough. However, in some accidents involving HD 1.3 materials, the complete combustion reaction occurred within the reaction time of the deluge system. In these cases, the deluge system could not prevent the initial deflagration but did extinguish the resultant fires. One possible method to defeat such a situation is to establish reaction zones for the sprinkler or deluge system that will inundate corridors and/or inhabited areas outside the room where the combustion occurs, not just inside that room. While this approach may not stop the deflagration, it could lessen the thermal effects threat downrange from the event. This could also extinguish any firebrands thrown clear of the event, thereby reducing the threat of propagation.

Operational Changes: Whenever an facility is being evaluated, changes in the operating procedures should be considered. For example, it is possible to eliminate the threat of injury to personnel simply by keeping persons far enough away, or in protected spaces, during hazardous operations in a specific area. Changes in type, quantity and locations of stored materials can also be considered. Changes in procedures can result in reduction or elimination of hazards without providing costly modifications to a structure.

Recommendations for Future Research

This design guide is based on a review of a limited number of existing test and accident reports, and on the procedures for designing structures to resist the effects of explosions.

Future work is required to refine the procedures in this design guide. This includes a further review of existing data and a program of testing the behavior of HD 1.3 materials burning in structures.

The procedures and recommendations provided herein are based on information in test and accident reports. Only a limited number of such reports were reviewed. An evaluation of additional test and accident reports may provide more specific, quantitative procedures for design, and this will at least confirm the procedures postulated in the design guide. More extensive data on HD 1.3 accidents is probably available from other sources, including non-US sources. The author encourages any readers who have knowledge of such data to contribute their knowledge to this effort.

Virtually all of the empirical data on combustion of HD 1.3 explosives is specific to individual materials and situations. There have been no test programs that address general behavior and attempt to quantify how most of these materials will behave. Therefore, any such research program will be of great value to the structural and facility design community. A test program has been proposed and should be performed to provide data to refine the procedures given in the design guide. This test program would include burning samples of HD 1.3 materials in scale model structures, in order to collect actual data of fireball volumes and gas pressures.

The test program should include an attempt to quantify the effect of relative degrees of confinement on the gas pressure and fireball effects, with the goal of defining the boundaries between unconfined, partially confined, and near fully confined events. These boundaries would be defined by vent ratio, ratio of charge weight ot volume, or some other relationships. A more rigorous definition of the F_1 factor, for use in the fireball expansion calculation procedure, should be persued. The goal of this effort will be to determine the relationships between the F_1 factor and confinement level, vent ratio, material type, and/or heat of combustion. Measurements of gas pressures and durations would validate the gas pressure calculation procedure or provide data on which a more realistic procedure can be based.

Different HD 1.3 materials exhibit different behavior in deflagrations. Propellants tend to burn more slowly than pyrotechnics. The test program should include more than one material, in order to begin to quantify this difference. It may be advantageous to select several "worst-case" materials to be used, or to engage in a test program to identify such materials. The phenomena exhibited by each test material during open, unconfined burning, including fireball volume and duration, should be evaluated. The effect of charge size should also be investigated. All conventional methods of design for explosions includes scaling based on the cube root of the weight of high explosives. The test program should include efforts to verify this scaling relationship for propellants and other HD 1.3 materials. Also, the size or weight of the charge has some effect on the gas pressure and thermal effects. This size effect should be studied by using several different charge weights in the tests. The relationships between charge weight and room volume, and between charge weight and vent area, should be investigated.

Availability of the Design Guide

The HD 1.3 Passive Structural Systems Design guide is currently available as technical report HNDED-CS-93-7 from the Huntsville Division, US Army Corps of Engineers. Copies can be obtained by writing to the address at Reference 7. It is intended that the design guide will be published as a DDESB technical paper, either in its current form or after more data are developed and test programs are performed.

Conclusions

The design of passive structural systems, to resist the effects of HD 1.3 explosives, is primarily a qualitative procedure. The precise behavior of these materials, when burning, in any given situation, cannot be accurately predicted. There is little empirical data on the behavior of HD 1.3 materials, and most of it is specific to a given munition, propellant or pyrotechnic mixture, and/or operation. The key to protecting personnel and assets from the effects of an HD 1.3 deflagration is simply to prevent those effects from reaching potentially exposed locations or personnel. This means providing either enough distance between the donor and receivers, or providing sufficient passive structural and architectural features to block the fire, overpressure, fragments and firebrands.

The criteria and procedures provided in the design guide will assist the user in designing facilities to provide adequate protection from events involving HD 1.3 explosives. The computational procedures in the design guide are believed to be reasonably conservative. However, the designer is reminded that these procedures do not take the place of either sound engineering judgement, or specific information about the HD 1.3 material in question, in any design application.

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